Radiations from High-Energy Positrons Incident on a Beryllium Target

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The energy spread and yields of nearly monoenergetic photons of various energies produced by the annihilation in flight of relativistic positrons have been experimentally determined using a 6-in.-long by 5-in.-diam NaI(Tl) crystal spectrometer. Photon lines with an energy spread of a few percent are reported. Yields of positrons and monoenergetic photons in the energy range from 2 Mev to 14 Mev have been measured. The bremsstrahlung spectra from 8.5-Mev positrons and electrons were compared and the yields and spectral distributions were found to agree within the experimental error.

INTRODUCTION

MUCH work has been done on the measurement of photonuclear reaction cross sections by use of bremsstrahlung radiation. The results have raised many new questions about details of the nature of the reactions that may be answered by further use of bremsstrahlung only by undertaking exceedingly laborious experiments. Much of the information needed could be obtained by use of a source of continuously variable, nearly monoenergetic photons having sufficient energy to examine regions through the giant resonances. The purpose of the work reported herein was to examine the feasibility of obtaining such a source of photons.

In this report is described the experimental production and observed yield of nearly monoenergetic gamma radiation of variable energy, produced by the annihilation in flight of positrons, using the Livermore Linear Accelerator facility.[1] Similar work was conducted simultaneously elsewhere.[2] The experiment described, which is a modification of one previously reported,[3] has permitted an appreciable reduction of backgrounds and an increase in the observed photon flux over that previously obtained. Positrons were produced by a cascade of photons and pairs initiated in a thick Ta target by bombardment with 20-Mev electrons. They appeared in a forward flux with energies distributed over a wide range. Positrons within a small energy interval were selected by collimation and magnetic analysis, then allowed to strike a thin Be target, where some of the positrons were annihilated in flight and produced a flux of nearly monoenergetic gamma radiation within a small solid angle in the forward direction. The observed line widths, photon yields, positron bremsstrahlung, scattering effects in the annihilation target, and effects introduced by collimation and beam energy analysis will be discussed.

THEORY

The production of electron bremsstrahlung and electron-positron pairs, such as occurred in the Ta target, is described by the theory of Bethe and Heitler.[4] The Dirac differential cross section for the annihilation in flight of a positron with an electron at rest is discussed by Kendall and Deutsch.[5] The relation between the energy k_A of the primary photon and its outgoing angle θ in the laboratory system is given as

$$k_A=\mu\left[1-\left(\frac{E-\mu}{E+\mu}\right)^{\frac{1}{2}}\cos\theta\right]^{-1}, \qquad (1)$$

where μ is the electron rest energy and E is the total energy of the incident positron. The fact that there is a one-to-one correspondence between energy and angle for the annihilation photons implies that an observation of the annihilation target at a given angle and aperture defines the energy and resolution of the observed photons. In attempting to see the annihilation radiation, one finds that the major competing process is positron bremsstrahlung. The differential cross sections at $\theta=0$ for both processes are comparable in magnitude for positrons having an energy of about 10-Mev incident on a target of low atomic number. However, most of the bremsstrahlung photons are in the low-energy region of the spectrum, and the high-energy limit of the bremsstrahlung spectrum, k_B, lies at the energy $k_B=E-\mu$. The energy of the annihilation quanta, k_A, may be obtained from Eq. (1) by letting $\cos\theta=1$. For 10-Mev incident positrons, k_A is 0.76 Mev greater than k_B. The photon spectrum of bremsstrahlung and annihilation radiation in the forward direction was computed for the case of 10-Mev positrons striking a thin beryllium target, using the Dirac theory, and is shown in Fig. 1.

Multiple scattering and straggling of positrons in the beryllium target will tend to broaden the annihilation peak. Using the Molière multiple scattering theory[6] and the energy-angle dependence of the annihilation cross section, it may be shown that the broadening due to scattering is less than about 0.1 Mev for 10-Mev

[1] N. A. Austin and S. C. Fultz, Rev. Sci. Instr. **30**, 284 (1959).
[2] J. Miller, C. Schuhl, G. Tamas, and C. Tzara, Compt. rend. **249**, 2543 (1959).
[3] C. P. Jupiter, N. E. Hansen, H. W. Koch, and S. C. Fultz, Bull. Am. Phys. Soc. **5**, 36 (1960).
[4] H. Bethe and W. Heitler, Proc. Roy. Soc. (London) **A146**, 90 (1934).
[5] H. W. Kendall and Martin Deutsch, Phys. Rev. **101**, 20 (1956); also J. W. Shearer, Ph.D. thesis, Massachusetts Institute of Technology, 1950 (unpublished).
[6] G. Molière, Z. Naturforsch. **3a**, 78 (1948).

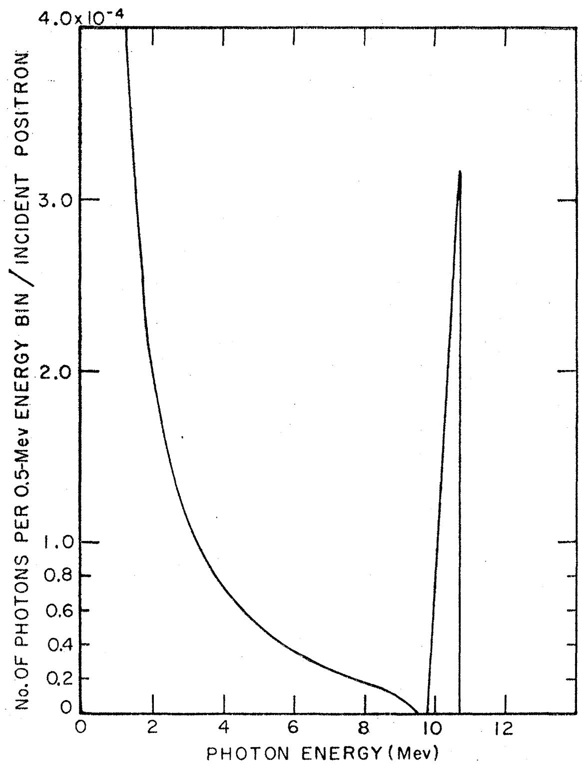

FIG. 1. Computed photon spectrum from 10-Mev positrons striking a 0.050-in.-thick beryllium target. The width at half maximum for this spectrum was taken to be 0.5 Mev.

positrons incident on a 0.050-in. beryllium target. The contribution to the energy broadening arising from energy straggling and energy loss of the positrons was estimated as follows. The energy loss in collisions averaged over all positrons passing through the target is approximately 0.4 Mev. The energy loss and straggling of only those positrons annihilating in flight within the target will be considerably smaller. Any remaining contribution to the linewidth can be attributed to the positron momentum interval, as determined by the analyzing magnets and collimators for the experiment. The latter effect was estimated by ray-tracing of the positron trajectories.

APPARATUS AND PROCEDURE

In Fig. 2 is shown a diagram of the layout of the experimental apparatus. The high-atomic-number target used for the source of positrons was Ta with a thickness approximately equal to the range of the incident 20-Mev electrons. Beryllium 0.050 in. thick was used for the annihilation target. This was enclosed in a vacuum box located between the poles of a beam-sweeping magnet, and could be rotated out of the positron beam path for background measurements. Spectra were observed with a 6-in.-long by 5-in.-diam NaI(Tl) crystal mounted on a DuMont-6364 photomultiplier tube, and were recorded on a 200-channel pulse-height analyzer. The analyzer was gated "on" simultaneously with the beam pulses.

Observed pulse-height spectra for photons obtained from the annihilation of 6-Mev positrons are shown in Fig. 3. The gamma-ray spectrometer consisted of the 6-in.-long by 5-in.-diam NaI(Tl) crystal mounted behind a 1-in.-diam lead collimator, 18 in. thick. The curve labeled "bremsstrahlung background" was obtained under the assumption that the shape of the positron bremsstrahlung spectrum is the same as that obtained from negative electrons of the same energy. To obtain the bremsstrahlung background curves, pulse-height distributions were taken under target-in and target-out conditions with magnet polarity reversed in order to select negative electrons. The bremsstrahlung background curve was fitted to the corrected annihilation spectrum in a region of small-amplitude pulses and subtracted. The resulting curve is assumed to represent the pulse-height distribution obtained from photons arising from only the annihilation-in-flight process.

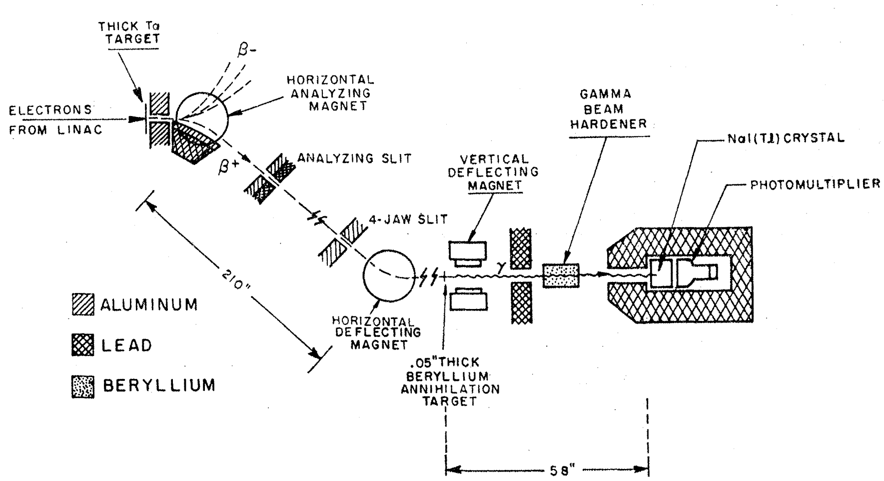

FIG. 2. Experimental layout for positron annihilation experiment.

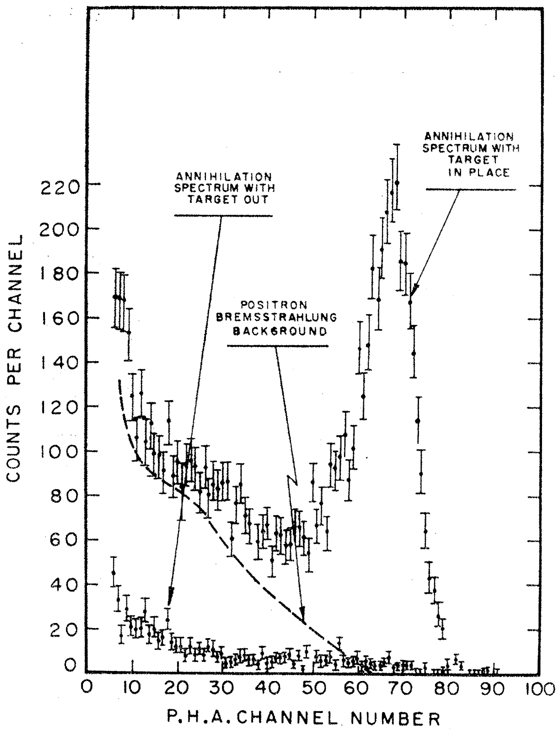

FIG. 3. Pulse-height spectrum and related backgrounds (detected by a 6-in.-long by 5-in.-diam NaI(Tl) crystal) for annihilation gammas from 6.0-Mev positrons incident on a 0.05-in.-thick beryllium target.

LINEWIDTHS

The measured widths at half maximum of the observed pulse-height spectra of positron annihilation in a 0.050-in. Be target are shown in Fig. 4. The figure shows also the widths of the response functions of the 6-in.-long by 5-in.-diam NaI(Tl) crystal spectrometer, as derived from observations of resonance-fluorescence gamma radiation with similar collimation.[7] When the crystal response is unfolded from the observed pulse-height spectra (by assuming Gaussian shapes and taking the root of the difference of the squares of the half-widths), the widths of the gamma lines incident on the spectrometer are obtained. These are plotted as a dotted line in Fig. 4. The dotted curve contains contributions to the linewidths that arise from (a) the positron momentum interval associated with the finite width of the beam-analyzing slit, and (b) positron energy loss and straggling in the annihilation target, and annihilation occurring after scattering, which might result in contributions to the photons in the forward direction by lower energy gamma rays.

A further experimental point, denoted by the dot in Fig. 4, corresponds to a measured linewidth obtained in a modified geometry in which the annihilation target and the detector were moved 16 ft farther from the second deflecting magnet and the Ta target was moved about 14 in. ahead of the first bending magnet. A set of quadrupole focusing magnets was inserted between the second bending magnet and the detector. It can be seen that the spectrometer linewidth measured in the new geometry corresponds closely to that obtained from the resonance-fluorescence measurements. This emphasizes that most of the broadening observed in the first measurements arose in imperfect magnetic analysis of the positron beam. The actual linewidth appears to be only a few percent of the photon energy.

A pulse-height spectrum was analyzed to obtain the spectral distribution of photons originating in the 0.050-in. thick beryllium target when bombarded by 10-Mev positrons. The background counts and the crystal response function of the annihilation photons were subtracted from the pulse-height spectrum. The bremsstrahlung spectrum was unfolded by use of the response matrix of Hubbel.[8] The area under the crystal response function for the annihilation photons was measured and the number of counts thus obtained. Both the bremsstrahlung spectrum and the number of observed annihilation photons were corrected for absorption in the 12-in. thick beryllium beam hardener and for the NaI crystal detection efficiency, thus giving the actual number of photons emitted. The number of annihilation counts was fitted to the area under a Gaussian curve having a chosen width at half maximum of 0.5 Mev. The photon spectrum from this analysis is shown in Fig. 5. Comparison with a predicted shape shown in Fig. 1 indicates reasonable agreement.

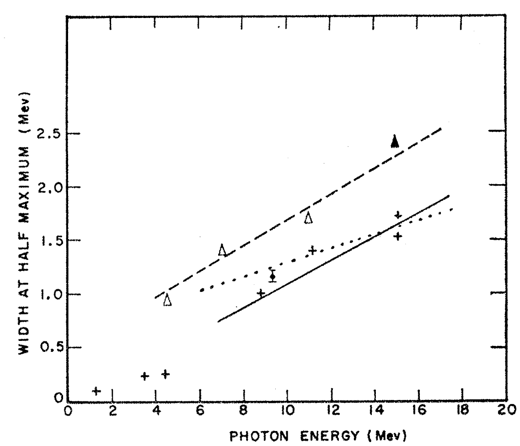

FIG. 4. Widths of gamma lines (using a 6-in.-long by 5-in.-diam NaI(Tl) crystal spectrometer). △, pulse-height spectrum of annihilation photons observed through a 1-in.-diam collimator; ▲, pulse-height spectrum of annihilation photons observed through a 2.25-in.-diam collimator; +, pulse-height spectrum of fluorescent gamma rays and radioactive sources observed through a 1-in.-diam collimator; ●, pulse-height spectrum of annihilation gamma rays observed through a 1-in.-diam collimator (modified geometry with 16-ft extension); · · · · ·, photon spectrum (i.e., crystal response function unfolded from the observed pulse-height data) of annihilation gamma rays observed through a 1-in.-diam collimator.

[7] F. D. Seward, H. W. Koch, R. E. Shafer, and S. C. Fultz, Bull. Am. Phys. Soc. 5, 68 (1960).

[8] J. H. Hubbel, Rev. Sci. Instr. 29, 65 (1958).

OBSERVED YIELDS

The observed yields of photons from the annihilation-in-flight process measured in the earlier geometry are presented in Fig. 6. The data are expressed in terms of the number of photons under the annihilation peak counted per minute, per kilowatt of power in the accelerator beam, per unit solid angle subtended in the forward direction at the Ta electron target, per unit solid angle subtended in the forward direction at the Be target. The momentum resolution of the analyzing magnet was about 2.5%. Corrections have been made for absorption in the Be beam hardener and counts arising from backgrounds and positron bremsstrahlung. The falling off of the curve at the lower photon energies is probably caused by the reduced positron-momentum interval chosen at these energies, and by the smallness of the annihilation differential cross section in this region. As the energy is increased the annihilation differential cross section and the yield increase, but at higher energies, i.e., near the tip of the spectrum of bremsstrahlung generated in the Ta target, the production of positrons declines.

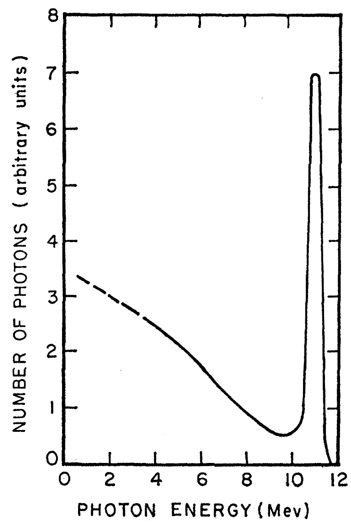

FIG. 5. Photon spectrum from 10-Mev positrons striking a 0.05-in.-thick beryllium target, unfolded from the pulse-height spectrum assuming a 0.5-Mev annihilation linewidth.

The observed positron yield, expressed in terms of the positron current in microamperes emitted from the Ta target per unit solid angle in the forward direction, per microampere of 20-Mev electrons in the accelerated beam, is shown in Fig. 7. The yields were measured in two ways: Some of the measurements were made with a Faraday cup located in a position closely following the second bending magnet. In order to make measurements of the positron current intermittently during the course of the experiment, a simpler portable detector consisting of a thick NaI(Tl) crystal mounted on a photomultiplier tube (which was calibrated against the Faraday cup) was used.

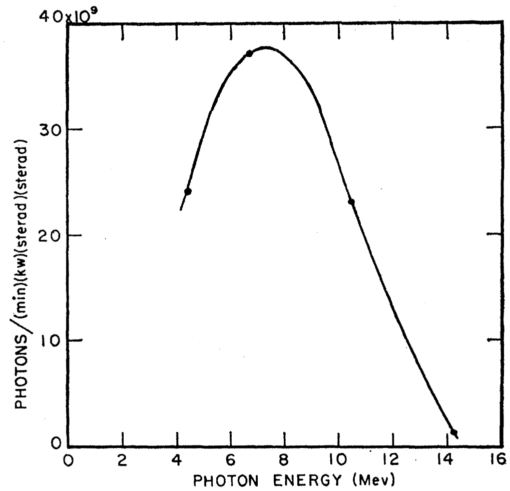

FIG. 6. Observed yields of photons from the annihilation in flight of positrons, in terms of the number of photons under the annihilation peak counted per minute per kilowatt of power in the accelerator beam, per unit solid angle subtended at the tantalum target in the forward direction, per unit solid angle subtended at the beryllium target in the forward direction.

POSITRON AND NEGATIVE-ELECTRON BREMSSTRAHLUNG

A comparison of the positron and negative-electron bremsstrahlung production is of value in determining the contribution of positron bremsstrahlung to effects observed with irradiation by annihilation photons. Earlier experimental work by Fisher,[9] using 247-Mev electrons and positrons on Au targets, indicates that the cross sections for bremsstrahlung production by these particles are essentially identical at this energy. It is of interest to compare the cross sections at a lower energy and under different conditions of nuclear screening.

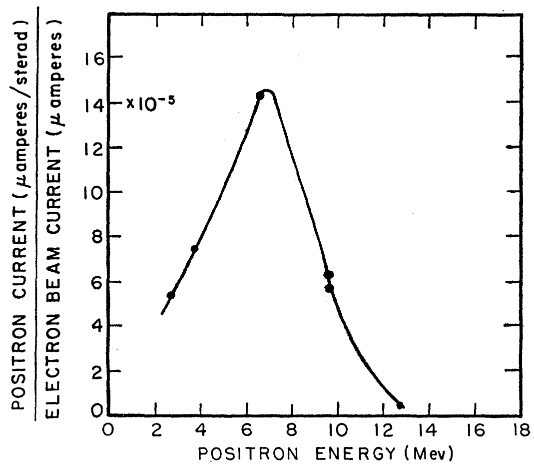

FIG. 7. Positron yield in microamperes per steradian in the forward direction per microampere of 20-Mev electrons on a thick tantalum target. The momentum resolution of the analyzer was about 2.5%.

[9] P. C. Fisher, Phys. Rev. 92, 420 (1953).

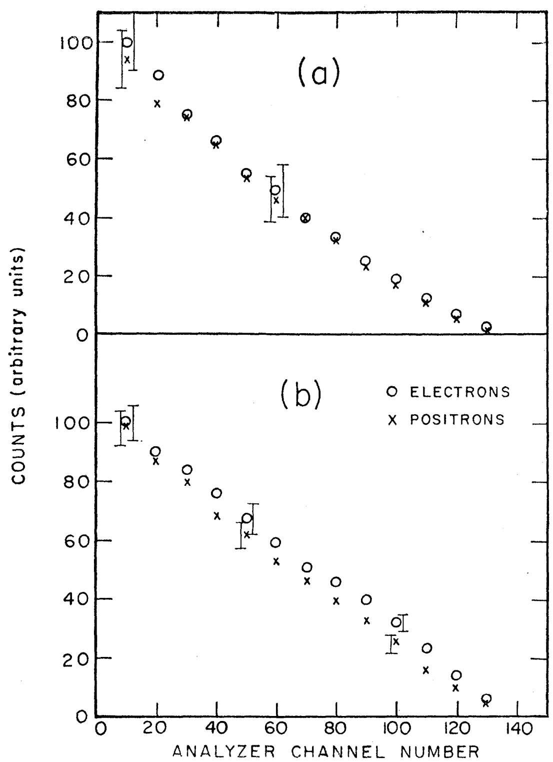

FIG. 8. Observed pulse-height spectra of bremsstrahlung for 8.5-Mev electrons and positrons, for (a) 0.030-in. beryllium target, (b) 0.003-in. tantalum target.

Data were obtained for the Be target used during the present work and for a thin Ta target introduced specifically to maximize the bremsstrahlung process. Gamma-ray pulse-height spectra were obtained for 8.5-Mev positrons and negative electrons incident on 0.030-in. thick Be and 0.003-in. Ta targets. At approximately five-minute intervals during the spectrum runs the beam was switched into a Faraday cup for measurements of the particle currents, and then magnetically deflected back to the target for further counting. Each run was about thirty minutes long. Additional runs were obtained under target-out conditions with each kind of particle to obtain backgrounds.

The observed pulse-height data were smoothed, then normalized to charges in the particle beams. Background spectra were subtracted from target-in spectra and annihilation peaks were removed by subtracting detector response functions scaled to the data. The resultant bremsstrahlung curves for positive and negative 8.5-Mev electrons incident on 0.030-in.-thick Be and 0.003-in. Ta targets are shown in Fig. 8. The errors in the data are caused by uncertainty of the crystal response function, statistical counting error, and fluctuations in the beam current. The over-all error was about 15%.

CONCLUSIONS

The properties of the radiations from high-energy positrons incident on a beryllium target have been examined. Yields of nearly monoenergetic annihilation photons have been measured, from which the accelerator and facility requirements for undertaking photonuclear experiments may be derived. The energy spread of the annihilation photons could not be accurately measured by the gamma spectrometer, but appeared to be a few percent of the photon energy when examined with good positron-beam optics. The yields per particle of positron and negative-electron bremsstrahlung appear to be the same within the errors of measurement.

ACKNOWLEDGMENTS

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